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FREE ELECTRON LASERS IN 2008

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Abstract
Thirty two years after the first operation of the free electron laser (FEL) at Stanford University, there continue to be many important experiments, proposed experiments, and user facilities around the world. Properties of FELs operating in the infrared, visible, UV, and x-ray wavelength regimes are listed and discussed.

The following tables list demonstrated (Table 1) and proposed (Table 2) relativistic free electron lasers (FELs) in 2008. A location or institution, followed by the FEL's name in parentheses, identifies each FEL; references are listed in Tables 3 and 4. Another good site for FEL references is http://sbfel3.ucsb.edu/www/vl_fel.html.

The first column of the table lists the operating wavelength λ, or wavelength range. The longer wavelengths are listed at the top with short x-ray wavelength FELs at the bottom of the table. The large range of operating wavelengths, seven orders of magnitude, indicates the flexible design characteristics of the FEL mechanism.

In the second column, σ_z is the electron pulse length divided by the speed of light *c*, and ranges from almost CW to short sub-picosecond pulse time scales. The expected optical pulse length in an FEL oscillator can be 3 to 5 times shorter or longer than the electron pulse depending on the optical cavity Q, the FEL desynchronism, and the FEL gain. The optical pulse can be up to 10 times shorter in the high-gain FEL amplifier. Also, if the FEL is in an electron storage-ring, the optical pulse is typically much shorter than the electron pulse. Most FEL oscillators produce an optical spectrum that is Fourier transform limited by the optical pulse length.

The electron beam energy E and peak current I are listed in the third and fourth columns, respectively. The next three columns list the number of undulator periods N, the undulator wavelength λ_0, and the rms undulator parameter $K=eB\lambda_0/2\pi mc^2$ (cgs units), where e is the electron charge magnitude, B is the rms undulator field strength, and m is the electron mass. For an FEL klystron undulator, there are multiple undulator sections as listed in the N-column; for example 2x33. Some undulators used for harmonic generation have multiple sections with varying N, λ_0, and K values as shown. Most undulators are configured to have linear polarization. Some FELs operate at a range of wavelengths by varying the undulator gap as indicated in the table by a range of values for K. The FEL resonance condition, $\lambda = \lambda_0(1+K^2)/2\gamma^2$, provides a relationship that can be used to relate the fundamental wavelength λ to K, λ_0, and $E=(\gamma-1)mc^2$, where γ is the relativistic Lorentz factor. Some FELs achieve shorter wavelengths by using harmonics.

The last column lists the accelerator types and FEL types, using the abbreviations listed at the bottom of the tables.

For the conventional oscillator, the peak optical power can be estimated by the fraction of the electron beam peak power that spans the undulator spectral bandwidth, 1/(2N), or $P \approx EI/(8eN)$. For the FEL using a storage ring, the optical power causing saturation is substantially less than this estimate and depends on ring properties. For the high-gain FEL amplifier, the optical power at saturation can be substantially greater than 1/(2N). The average FEL power is determined by the duty cycle, or spacing between the electron micropulses, and is typically many orders of magnitude lower than the peak power. The JLab infrared FEL has now reached an average power of 14 kW with the recovery of the electron beam energy in superconducting accelerator cavities.

In the FEL oscillator, the optical mode that best couples to the electron beam in an undulator of length $L=N\lambda_0$ has Rayleigh length $z_0 \approx L/12^{1/2}$ and has a mode waist radius of $w_0 \approx N^{1/2}\gamma\lambda/\pi$. The FEL optical mode typically has more than 90% of the power in the fundamental mode described by these parameters.

This year the DESY FLASH FEL has reached the shortest wavelength ever for an FEL, $\lambda \approx 6.5$ nm. There was one other new lasing at Kyoto (KU-FEL) at $\lambda \approx 11$-14 μm.

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Table 1: Demonstrated Free Electron Lasers (2008)

LOCATION (NAME)	λ(μm)	σ_z(ps)	E(MeV)	I(A)	N	λ_0(cm)	K(rms)	
Frascati (FEL-CAT)	760	15-20	1.8	5	16	2.5	0.75	RF,O
UCSB (mm FEL)	340	25000	6	2	42	7.1	0.7	EA,O
Novosibirsk (RTM)	120-230	70	12	10	2x33	12	0.71	ERL,O
KAERI (FIR FEL)	97-1200	25	4.3-6.5	0.5	80	2.5	1.0-1.6	MA,O
Osaka (ISIR,SASE)	70-220	20-30	11	1000	32	6	1.5	RF,S
Himeji (LEENA)	65-75	10	5.4	10	50	1.6	0.5	RF,O
UCSB (FIR FEL)	60	25000	6	2	150	2	0.1	EA,O
Osaka (ILE/ILT)	47	3	8	50	50	2	0.5	RF,O
Osaka (ISIR)	32-150	20-30	13-19	50	32	6	1.5	RF,O
Tokai (JAEA-FEL)	22	2.5-5	17	200	52	3.3	0.7	RF,O
Bruyeres (ELSA)	20	30	18	100	30	3	0.8	RF,O
Dresden (U-100)	18-230	5-20	20-40	25	38	10	2.8	RF,O
Osaka (FELI4)	18-40	10	33	40	30	8	1.3-1.7	RF,O
LANL (RAFEL)	15.5	15	17	300	200	2	0.9	RF,O
Kyoto (KU-FEL)	11-14	2.0	25	17	40	4	0.99	RF,O
Darmstadt (FEL)	6-8	2	25-50	2.7	80	3.2	1	RF,O
Osaka (iFEL1)	5.5	10	33.2	42	58	3.4	1	RF,O
BNL (HGHG)	5.3	6	40	120	60	3.3	1.44	RF,A
Beijing (BFEL)	5-20	4	30	15-20	50	3	1	RF,O
Dresden (ELBE)	4-22	1-10	34-16	30	2x34	2.73	0.3-0.7	RF,O,K
Tokyo (KHI-FEL)	4-16	2	32-40	30	43	3.2	0.7-1.8	RF,O
Nieuwegein (FELIX)	3-250	1	50	50	38	6.5	1.8	RF,O
Orsay (CLIO)	3-53	0.1-3	21-50	80	38	5	1.4	RF,O
KAERI (HP FEL)	3-20	10-20	20-40	30	2x30	3.5	0.5-0.8	RF,O,K
Osaka (iFEL2)	1.88	10	68	42	78	3.8	1	RF,O
Nihon (LEBRA)	0.9-6.5	<1	58-100	10-20	50	4.8	0.7-1.4	RF,O
UCLA-BNL (VISA)	0.8	0.5	64-72	250	220	1.8	1.2	RF,S
JLab (IR upgrade)	0.7-10	0.15	120	400	30	5.5	3	ERL,O
BNL (ATF)	0.6	6	50	100	70	0.88	0.4	RF,O
Duke (OK-5)	0.45	0.1-10	270-800	35	2x32	12	0-4.75	SR,O,K
Dortmund (FELICITAI)	0.42	50	450	90	17	25	2	SR,O
Osaka (iFEL3)	0.3-0.7	5	155	60	67	4	1.4	RF,O
Orsay (Super-ACO)	0.3-0.6	15	800	0.1	2x10	13	4.5	SR,O,K
BNL (SDL FEL)	0.2-1.0	0.5-1	100-250	300-400	256	3.9	0.8	RF,A,S,H
Okazaki (UVSOR)	0.2-0.6	6	607	10	2x9	11	2	SR,O,K
Tsukuba (NIJI-IV)	0.2-0.6	14	310	10	2x42	7.2	2	SR,O,K
Trieste (ELETTRA)	0.2-0.4	28	1000	150	2x19	10	4.2	SR,O,K
Duke (OK-4)	0.193-2.1	0.1-10	1200	35	2x33	10	0-4.75	SR,O,K
RIKEN (SCSS Prototype)	0.03-0.06	1	250	300	600	1.5	0.3-1.5	RF,S
DESY (FLASH)	0.0065	0.025	1000	2000	984	2.73	0.81	RF,S

MA - Microtron Accelerator
EA - Electrostatic Accelerator
SR - Electron Storage Ring
ERL - Energy Recovery Linear Accelerator
RF - Radio-Frequency Linear Accelerator

A - FEL Amplifier
O - FEL Oscillator
K - FEL Klystron
S - Self-Amplified Spontaneous Emission (SASE) FEL
H - High-Gain Harmonic Generation (HGHG) FEL

Table 2: Proposed Free Electron Lasers (2008)

PROPOSED FELs	**λ(μm)**	**σ_z(ps)**	**E(MeV)**	**I(A)**	**N**	**λ_0(cm)**	**K(rms)**	
Tokyo (FIR-FEL)	300-1000	5	10	30	25	7	1.5-3.4	RF,O
Nijmegen (THz-FEL)	100-1500	3	10-15	50	40	11	0.5-3.3	RF,O
Novosibirsk (RTM1)	5-100	10	50	20-100	3x33	6	2	ERL,O
Monterey (NPS FEL)	4-20	5	40	100	50	2	1	ERL,O
Novosibirsk (RTM)	2-11	20	98	100	4x36	9	1.6	ERL,O
Frascati (SPARC)	0.5	0.3	155	700	6x75	2.8	1.5	RF,S,H
Hawaii (FEL)	0.3-3	2	100	500	84	2.4	1.2	RF,O
Shanghai (SDUV-FEL)	0.26	2-3	160	300	360	2.5	1.025	RF,S,H
JLab (UV FEL)	0.25-1	0.2	160	270	60	3.3	1.3	ERL,O
Harima (SUBARU)	0.2-10	26	1500	50	33,16	16,32	8	SR,O,K
PROPOSED FELs	**λ(nm)**	**σ_z(ps)**	**E(GeV)**	**I(kA)**	**N**	**λ_0(cm)**	**K(rms)**	
Shanghai (SDUV-FEL)	88	~2	280	400	360	2.5	1.025	RF,S,H
Rome (SPARX 1)	10-30	0.2-0.01	0.96-1.5	1	715	3.4	0.2-2.32	RF,S
ARC-EN-CIEL (LEL3)	8-40	~1	1-2	0.2-1	350	3.0	2.4	RF,O
ARC-EN-CIEL (LEL1)	1.5-200	~1	0.22-1	~1	200 700	2.6 3	2.3 1.6	RF,H
BESSY (Soft X-ray)	1.2	0.08	2.3	3.5	1450	2.75	0.9	RF,S
Rome (SPARX 2)	1-14	0.2-0.01	0.96-2.6	1-2.3	220 900 400	4.0 2.8 2.2	3.1 1.63 1.34	RF,S
Trieste (FERMI)	1-100	0.1	1.2	0.5-2.5	1140	3.5	1.2	RF,S
Wisconsin (WiFEL)	1	0.1	2.2	1	10 30 900	8.0 5.5 3.3	1.0	RF,H
Rome (SPARX 3)	0.6-1.6	0.2-0.01	1.5-2.4	2.3	2520	1.5	0.91	RF,S
ARC-EN-CIEL (LEL2)	0.5-1	~1	0.8-1.2	~1	500 500	2.6 1.8	2.3 2.2	RF,H
MIT (Bates X-Ray FEL)	0.3	0.05	4	1	1500	1.8	2	RF,S
ARC-EN-CIEL (LEL4)	0.2-2	~1	3	~1	700 1000	3.5 1.8	3.4 2.2	RF,H
SLAC (LCLS)	0.15	0.07	14.4	3.4	3328	3	3.7	RF,S
DESY (XFEL)	0.1	0.08	17.5	5	4700	3.6	3.2	RF,S
Pohang (PAL X-FEL)	0.1	0.23	10	3.4	4500	2.23	1.57	RF,S
RIKEN (SPring8 SCSS)	0.1	0.5	8	2	1500	1.5	1.3	RF,S

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K - FEL Klystron
S - Self-Amplified Spontaneous Emission (SASE) FEL
H - High-Gain Harmonic Generation (HGHG) FEL

Table 3: References and Websites for Demonstrated FELs

LOCATION (NAME)	Internet Site or Reference
Beijing (BFEL)	http://www.ihep.ac.cn/english/BFEL/index.htm
BNL (ATF)	K. Batchelor et. al., NIM **A318**, 159 (1992).
BNL (HGHG)	A. Doyuran et. al., NIM **A475**, 260 (2001).
BNL (SDL FEL)	http://sdl.nsls.bnl.gov/
Bruyeres (ELSA)	P. Guimbal et. al., NIM **A341**, 43 (1994).
Darmstadt (FEL)	http://www.ikp.physik.tu-darmstadt.de/richter/fel/
DESY(FLASH)	http://flash.desy.de
Dortmund (FELICITAI)	http://www.delta.uni-dortmund.de/pub/fel/FEL.html
Dresden (ELBE)	http://www.fz-rossendorf.de
Dresden (U-100)	http://www.fz-rossendorf.de
Duke (OK-5)	http://www.fel.duke.edu
Frascati (FEL-CAT)	A. Doria et. al, Phys. Rev. Lett. **80**, 2841 (1998).
Himeji (LEENA)	T. Inoue et. al., NIM **A528** 402 (2004).
JLab (IR upgrade)	http://www.jlab.org/FEL
KAERI (FIR FEL)	http://epaper.kek.jp/a01/PDF/TUBM03.pdf
KAERI (HP FEL)	http://epaper.kek.jp/a01/PDF/TUBM03.pdf
Kyoto (KU-FEL)	http://wonda.iae.kyoto-u.ac.jp/index-e.html
LANL (RAFEL)	http://accelconf.web.cern.ch/AccelConf/l00/papers/TH301.pdf
Nieuwegein (FELIX)	http://www.rijnh.nl/n4/n3/f1234.htm
Nihon (LEBRA)	http://accelconf.web.cern.ch/AccelConf/f07/PAPERS/MOPPH046.PDF
Novosibirsk (RTM)	http://www.inp.nsk.su/activity/preprints/files/2003_053.pdf
Okazaki (UVSOR)	http://accelconf.web.cern.ch/AccelConf/a01/PDF/WEP014.pdf
Orsay (CLIO)	http://clio.lcp.u-psud.fr/clio_eng/clio_eng.htm
Orsay (Super-ACO)	M. E. Couprie et. al., NIM **A407**, 215-220 (1998).
Osaka (FELI4)	T. Takii et. al., NIM **A407**, 21-25 (1998).
Osaka (iFEL1)	http://accelconf.web.cern.ch/AccelConf/f04/papers/THPOS17/THPOS17.PDF
Osaka (iFEL2)	http://accelconf.web.cern.ch/AccelConf/f04/papers/THPOS17/THPOS17.PDF
Osaka (iFEL3)	http://accelconf.web.cern.ch/AccelConf/f04/papers/THPOS17/THPOS17.PDF
Osaka (ILE/ILT)	N. Ohigashi et. al., NIM **A375**, 469 (1996).
Osaka (ISIR)	http://accelconf.web.cern.ch/AccelConf/f07/PAPERS/FRAAU04.PDF
RIKEN(SCSS Prototype)	http://www-xfel.spring8.or.jp
Tokai (JAEA-FEL)	R. Hajima et. al., NIM **A507**, 115 (2003).
Tokyo (KHI-FEL)	M. Yokoyama et. al., NIM **A475**, 38 (2001).
Trieste (ELETTRA)	http://www.elettra.trieste.it/projects/euprog/fel
Tsukuba (NIJI-IV)	K.Yamada et. al., NIM **A475**, 205 (2001).
UCLA-BNL (VISA)	A. Tremaine et. al., NIM **A483**, 24 (2002).
UCSB (FIR FEL)	http://sbfel3.ucsb.edu
UCSB (mm FEL)	http://sbfel3.ucsb.edu

Table 4: References for Proposed FELs

LOCATION (NAME)	References for Proposed FELs
ARC-EN-CIEL FEL	http://accelconf.web.cern.ch/AccelConf/f07/PAPERS/FRAAU01.PDF
BESSY (Soft X-ray)	M. Abo-Bakr et. al., Nucl. Inst. and Meth. **A483**, 470 (2002); Tsukuba Mo-P-07,Mo-P-08,We-P-51 (Sept 2003).
DESY (XFEL)	http://www.xfel.net
Frascati (SPARC)	http://www.sparc.it
Harima (SUBARU)	http://epaper.kek.jp/a98/APAC98/6A004.PDF
Hawaii (FEL)	R. J. Burke et al, Proc. SPIE: Laser Power Beaming, Los Angeles, Jan. 27-28, 1994, Vol **2121**.
JLab (UV FEL)	S. Benson et. al., Nucl. Inst. and Meth. **A429**, 27-32 (1999).
MIT (Bates X-Ray FEL)	http://filburt.lns.mit.edu/xfel
Monterey (NPS FEL)	J.W. Lewellen, et. al., Status of the NPS Free Electron Laser, Proc. 2008 Lin. Acc. Conf., http://www.jacow.org.
Novosibirsk (RTM)	N. G. Gavrilov et. al., Status of Novosibirsk High Power FEL Project, SPIE Proceedings, vol. **2988**, 23 (1997); N. A. Vinokurov et. al., Nucl. Inst. and Meth. **A331**, 3 (1993).
Novosibirsk (RTM1)	V. P. Bolotin et. al., Nucl. Inst. and Meth. **A475**, II-37 (2001).
Pohang (PAL X-FEL)	Presented at FEL 2008, these Proceedings, http://www.jacow.org.
RIKEN (SPring8 SCSS)	T. Shintake et. al., Nucl. Inst. and Meth. A507, 382 (2003); http://www-xfel.spring8.or.jp
Rome (SPARX)	http://accelconf.web.cern.ch/AccelConf/f07/PAPERS/MOPPH058.PDF
Shanghai (SDUV-FEL)	Z. T. Zhao et. al, Nucl. Inst. and Meth. **A528**, 591 (2004).
SLAC (LCLS)	M. Cornacchia, Proc. SPIE 2998, 2-14 (1997); LCLS Design Study Report, SLAC R-521 (1998).
Tokyo (FIR-FEL)	H. Koike et. al., Nucl. Inst. and Meth. **A483**, II-15 (2002).
Trieste (FERMI)	http://www.elettra.trieste.it/FERMI
Wisconsin (WiFEL)	www.wifel.wisc.edu